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14. ABSTRACT

The objective of the project is to investigate the potential of cellular structures for the design of structural components with superior, new and multifunctional characteristics. In particular, the project focuses on a new topology, the chiral topology, which provides the cellular assembly with unique mechanical properties which include a negative in-plane Poisson's ratio, a correspondingly high shear modulus, high displacement capabilities in the elastic range of the material, and large design flexibility, whereby properties and behavior of the assembly can be significantly altered through variations in its characteristic geometric parameters. The applications that have so far been considered include sandwich panels with honeycomb core, and

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Application of Chiral Cellular Structures for the Design of Innovative Structural Assemblies

FINAL REPORT

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List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. J. Martin, J.-J. Heyder-Bruckner, C. Remillat, F. Scarpa, K. Potter, M. Ruzzene "The hexachiral prismatic wingbox concept", Accepted Phys. Stat. Sol. (b), 1– 8 (2008) .

2. Spadoni A., Ruzzene M., "Numerical and Experimental Analysis of The Static Compliance of Chiral Truss-Core Airfoils" Journal of Mechanics of Materials and Structures, Vol. 2(5) pp. 965, 2007.

3. M. R. Hassan, F. Scarpa, M. Ruzzene and M. N. Mohammed. "Smart shape memory alloy chiral honeycomb". Materials Science and Engineering A. In press.

4. Spadoni A., Ruzzene M., 2006 "Static Aeroelastic Response of Chiral Truss-core Airfoils" Journal of Intelligent Material Systems and Structures, 5 2007.

5. Spadoni A., Ruzzene 2006 "Structural and Acoustic Behavior of Chiral Truss-Core Beams" ASME Journal of Vibration and Acoustics, v 128, n 5, Oct. 2006, p 616-26.

6. Spadoni A., Ruzzene M., Scarpa F., 2006 "Dynamic Response of Chiral Truss-core Assemblies" Journal of Intelligent Materials and Structures, v 17, n 11, November, 2006, p 941-952.

7. Scarpa F., Blain S., Lew T., Perrott D., Ruzzene M., and Yates J. R., 2006 "Analytical And Experimental Analysis On The Elastic Buckling Of Hexagonal Chiral Cell Honeycombs" Composites Part A: Applied Science and Manufacturing Volume 38, Issue 2 , February 2007, Pages 280-289.

8. Scarpa F., Pastorino P., Garelli A., Patsias S., Ruzzene M., 2005 "Auxetic Compliant Flexible PU Foams: Static and Dynamic Properties" Physica Status Solidi B 242, No. 3, 681–694.

9. Spadoni A., Ruzzene M., Scarpa F., 2005 "Global and Local Linear Buckling Of Chiral Cellular Structures" Physica Status Solidi B 242, No. 3, 695–709.

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(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

1.   M. Ruzzene, Spadoni A., Scarpa F., "Application of Chiral Structures to Morphing Airfoils", Proceeding of Auxetics2006, Exeter, UK, September 2006.
2.   F. Scarpa, Hassan M.R., Ruzzene M. "Modeling and testing of shape memory alloy chiral honeycomb structures", Proceedings of the Smart Materials and Structures Conference, San Diego CA, March 2006.
3.   Spadoni A., Ruzzene M., "Static Aeroelastic Response of Chiral Truss-core Airfoils", Proceedings of the ICAST05 Conference, Paris, France, October 2005.
4.   Lew T., Spadoni A., Ruzzene M., Scarpa F., "Chiral hexagonal cellular sandwich structure: a vibroacoutic assessment"" Proceedings of the Smart Materials and Structures Conference, San Diego CA, March 2005.
5.   Spadoni A., Ruzzene M., Scarpa F., "Dynamic Response of Chiral Truss-core Assemblies" Proceedings of the Smart Materials and Structures Conference, San Diego CA, March 2005.
6.   Spadoni A., Ruzzene M., Scarpa F., "Chiral Truss-Core Beams With Selective Actuation Capabilities For Shape And Vibration Control." Proceedings of the ICAST04 Conference, Bar Harbor ME, October 2004.

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):   6

Peer-Reviewed Conference Proceeding publications (other than abstracts):

1.   Spadoni A., Ruzzene M., "Experimental Investigation of Static Morphing of Chiral Core Airfoils", Proceedings of the IMECE06 Conference, Chicago IL, November 2006.
2.   Spadoni A., Ruzzene M., "Buckling and Thermal Behavior of Chiral Honeycombs." Proceedings of the IMECE05 Conference, Orlando FL, November 2005.
3.   Spadoni A., Ruzzene M., "Structural and Acoustics Behavior of Chiral Truss-core Beams." Proceedings of the IMECE04 Conference, Anaheim, CA, November 2004.

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(d) Manuscripts

Chiral Structures as phononic metamaterials - in preparation

Number of Manuscripts: 1.00

Number of Inventions:

Graduate Students

NAME	PERCENT SUPPORTED	
Alessandro Spadoni	1.00	
FTE Equivalent:	**1.00**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED	
Stefano Gonella	0.20	
FTE Equivalent:	**0.20**	
Total Number:	**1**	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Massimo Ruzzene	0.25	No
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT SUPPORTED
Alex Gavrilovski	0.20
Maria Galvis	0.20
Alessandro Spadoni	0.20
FTE Equivalent:	**0.60**
Total Number:	**3**

Student Metrics
This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 3.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:······ 3.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:······ 3.00

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Names of Personnel receiving masters degrees

NAME
Alessandro Spadoni
Total Number: 1

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

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Application of Chiral Cellular Structures for the Design of Innovative Structural Assemblies

ARO Project Number 45518-EG

FINAL REPORT

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2/14/2008

Table of contents

1. Project Overview

The objective of the project is to investigate the potential of the chiral topology shown in Figure 1 for the design of innovative structural components. The applications that have so far been considered include sandwich panels with honeycomb core (Figure 2), and truss-core airfoils (Figure 3). Advantages with respect to current designs, and multi-functionality are particularly investigated. This structural arrangement provides the cellular assembly with unique mechanical properties which include a negative in-plane Poisson's ratio, a correspondingly high shear modulus, high displacement capabilities in the elastic range of the material, and large design flexibility, whereby properties and behavior of the assembly can be significantly altered through variations in its characteristics geometric parameters.
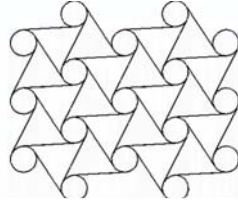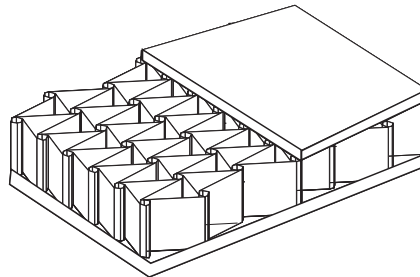

Figure 1 – Chiral geometry
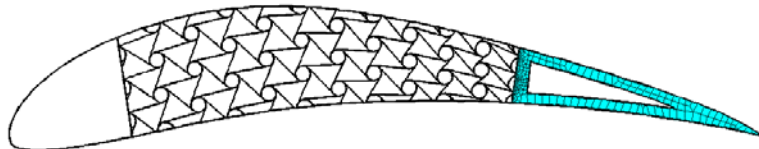

Figure 2 – Chiral honeycombs

Figure 3 – Airfoil with chiral truss-core

2. Approach

The objectives of the project are being achieved through numerical simulations, experimental validations as well as analytical models. Numerical simulations are currently being employed to validate recently obtained analytical models. Such codes are also used in support of the design of experimental specimens. The technical barriers that are being addressed by the project can be summarized as follows:

- *Application to morphing airfoils*. In recent years, a variety of solutions have been studied to provide aircraft wings and blades with adaptive capabilities. Challenges are associated to the conflicting requirements of a structure to be able to carry mechanical loads, while preserving the capability of adapting to changing operating conditions or to specified control inputs. A chiral cellular network replacing the rib is here proposed as an alternative design for airfoil morphing.

- *Mechanical characterization*. Brief description of chiral topologies can be found in previous work on cellular structures, however the full mechanical characterization of their properties is still lacking. This is being undertaken as part of this project. A complete analysis of the mechanical behavior of chiral structures is required in order to fully understand the fundamentals of their behavior and to demonstrate their effectiveness and multifunctionality. Such a study needs to include a thorough characterization of the in-

plane and out-of-plane mechanical properties. The mechanical characterization has been the focus of the activities during the last reporting period.

- *Application for new sandwich configuration.* Sandwich structures are generally lightweight but provide good strength capabilities. They find application in numerous engineering structures. This project investigates a new configuration which may provide superior mechanical properties as well as potentials for multifunctional capabilities. The combination of mechanical properties and advantageous heat dissipation capabilities for example, may lead to advanced thermal protection systems with load carrying capabilities. Traditional hexagonal honeycomb designs provide limited design flexibility, and improvements will require the study of new honeycomb geometries, such as the kind investigated in this project.

- *Enhancement of Mechanical Properties via Composite Materials.* As the mechanical behavior of chiral honeycombs emerges from studies carried out in the current reporting period, it has become apparent that the employment of composite materials may enhance the positive characteristics, such as the ability of chiral honeycombs to undergo large displacements while in the linear portion of stress-strain relationships. Composites may further enhance advantages of the truss core airfoils previously presented, such as higher deformation capabilities, increases in load carrying ability, and the elastic coupling of deformation mechanisms. Such improvements, observed in preliminary numerical investigations, will have to be thoroughly quantified before technology transfer. The possibility of employing composite materials has been the focus of the current reporting period alongside the thorough characterization of the mechanical behavior.

- *Manufacturing:* Advancements in the area of materials and structures need to be supported by developments in the manufacturing processes to allow the design of various geometries. One of the main challenges encountered during this project is related to difficulty in manufacturing prototypes for experimental validations of the concepts under investigation. Initial samples have been manufactured and tested, using equipment purchased under an ARO-funded DURIP grant supporting this effort. In this last reporting period, additional manufacturing techniques have been investigated which allow the use of composite materials. The design flexibility of composite materials can supplement that of the chiral geometry which may be jointly exploited to achieve functionally graded properties through the assembly, and/or to embed actuating devices, such as shape memory fibers and piezoelectric laminae, for active shape control applications. A sample chiral cell has been manufactured using carbon fiber composites to demonstrate the feasibility of the developed manufacturing process.

3. Impact of The Research

The application of this novel cellular geometry will lead to the development of structural components with superior elastic and impact resilient properties. Such mechanical characteristics can be also complemented by attractive multifunctional features. Optimal chiral configurations may be found for sandwich components which need to operate in harsh loading and thermal environments. Examples of multifunctional applications of the considered concepts include:

- *Morphing airfoils* with static and dynamic shape control capabilities

- *Thermal Protection Systems (TPS) using metallic honeycombs.* Metallic honeycombs have been proposed for many military applications, particularly those in which a high temperature, high strength-to-weight ratio is a requirement. The design flexibility offered by the chiral topology can lead to configurations showing both optimal structural and heat protection performance.

- *Acoustic panels.* The acoustic transmission characteristics of chiral panels has been analyzed numerically, while experimental validations are in the planning stages. The intervening voids may be exploited to enhance the sound absorption characteristics of the panels without compromising their structural integrity.

- *Energy absorbing sandwich panels.* Based on the initial investigations, modified designs can be investigated to enhance the energy absorption capabilities of the chiral configuration.

- *Composite cellular structures with embedded actuation and functionally graded properties for shape control applications.*

The project supports the development of lightweight multi-functional structural components, which can be used to improve the reliability and the durability of ground and air vehicles. The compliant airfoils may be used as part of adaptive rotor blades or on fixed-wing aircraft. The crashworthy chiral honeycomb designs can be directly transitioned and employed as part of helicopter fuselage and sub-floors, or of armored vehicles. Their high energy absorption capabilities may be complemented by high durability under elevated temperatures to provide

critical protection to personnel operating the vehicles. Acoustic and vibration insulation characteristics can reduce noise and fatigue of critical components. A number of Army Research Laboratory (ARL) projects will benefit from the findings of the research. Some of these projects include the ``Research on advanced aircraft structural concepts", ``Impact damage resistance and tolerance of thin skin composite sandwich structures", ``Crashworthiness of composite frames and floor sections", and ''Innovative composite fuselage design for improved crashworthiness" programs. Furthermore, this work can be integrated in the research activities on integrated advanced manufacturing processes for improved strength and stiffness-critical performance of rotorcraft structures, and as an example of sandwich concepts for light-weight helicopter applications.

4. Research Accomplishments on Morphing Airfoils

4.1. Passive morphing of a truss-core airfoil.

In recent years, a variety of solutions have been studied to provide aircraft wings and blades with adaptive capabilities. A chiral cellular network replacing the rib is here proposed as an alternative design for airfoil morphing (Figure 3). The proposed configuration is an attempt to obtain compliance while preserving the sound structural integrity of the wing component. In addition, the design flexibility of the chiral structure can be exploited to select the compliance as dictated by specific design needs. This concept has been investigated through numerical models. The deformation characteristics of the chiral structure, consisting in a combination of bending/axial deformation of the ligaments and rotation of the nodes, are utilized to obtain the required flexibility that allows modifying the mean camber line in response to changing pressure distributions on the airfoil. The airfoil deformation needs to occur in the elastic range of the constitutive material, so that it can be fully recovered. The performance of an Eppler 420 airfoil is investigated for chiral cores with various values of the L/R ratio. The airfoil structure is discretized using finite elements to predict its deformation resulting from a given pressure distribution. An iterative process is implemented to obtain convergence for both aerodynamic loads, estimated through CFD calculations, and structural displacements. The iterations are needed since the aerodynamic loads depend on the chordwise displacements of the chiral-core airfoil, which in turn depend on the aerodynamic loads. Examples of deflected configurations are shown in Figure 5, where deflections are represented in full scale, with no amplification nor reduction applied to the plots. The two figures show the response of two chiral cores, respectively with L/R=0.7 and L/R=0.9, for the same flow conditions on the airfoil (Mach number M=0.45, angle of attack α=2°). These results show how the behavior of the airfoil changes significantly as the design of the core is modified through simple selection of a given L/R ratio. In the first case, the airfoil is obviously very stiff, while in the second the core compliance generates an evident camber change.
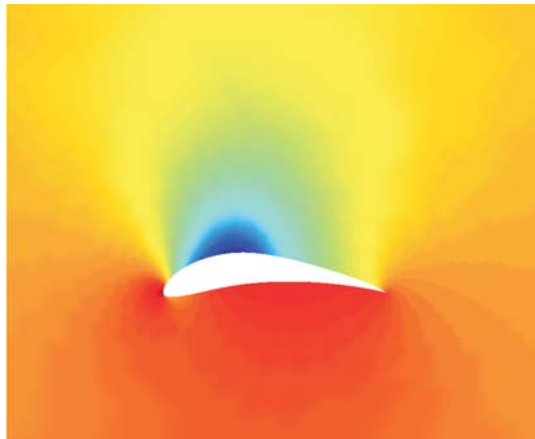

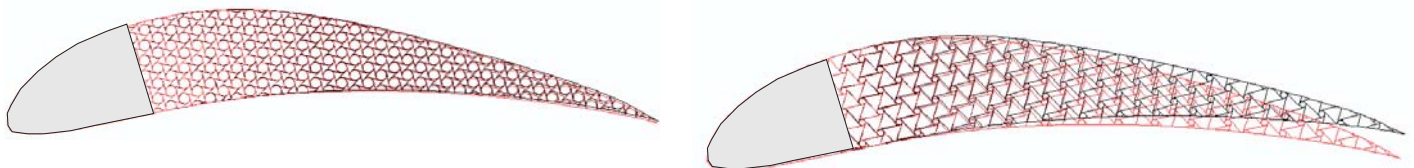Figure 4 – Pressure distribution around the airfoil

Figure 5 - Deformed configurations for airfoils with different core designs: L/R=0.7, L/R=0.9

The numerical predictions have been compared to experimental measurements performed on airfoil aluminum samples manufactured on the basis of an Eppler 420 section (see Figures 3, 6). All three manufactured airfoil configurations have a chord of 0.7 *m* and a maximum thickness of 8.7 *cm*. Such dimensions where chosen to satisfy manufacturing constraints. The objective of the experiments is to assess the ability of the chiral core to sustain large deformations while remaining within the elastic range of the constitutive material.
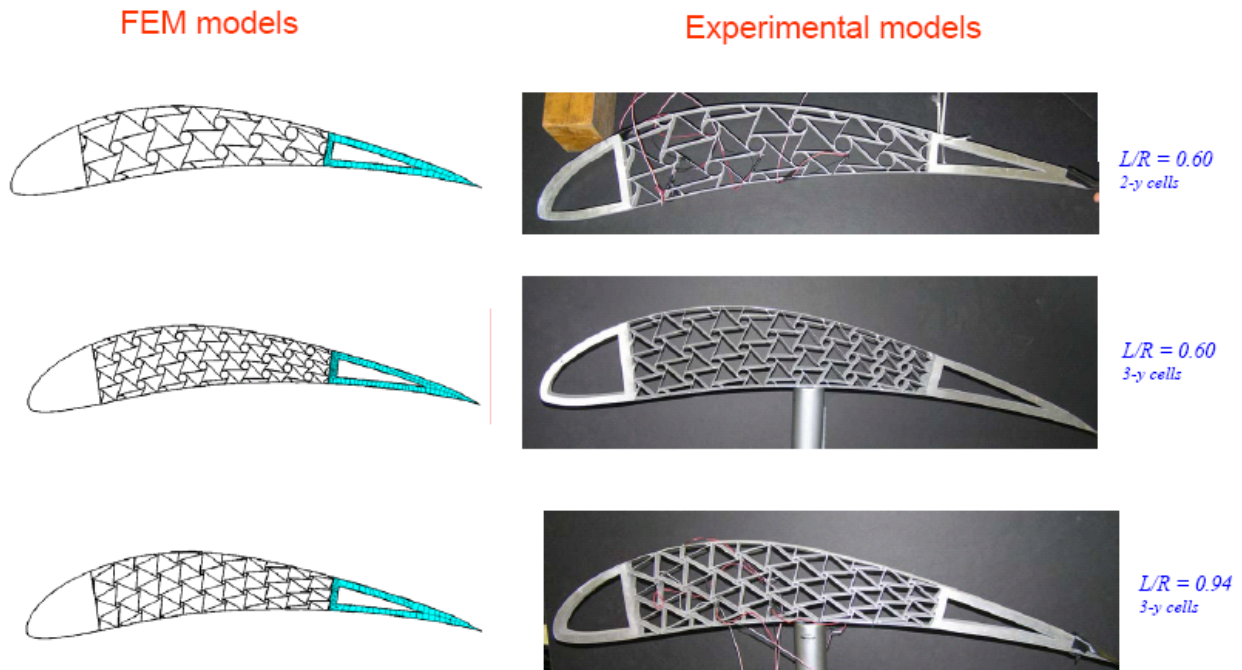
Figure 6 - Numerical models and test samples used for the evaluation of the static morphing characteristics of chiral airfoils

The comparison between deflections obtained for the three designs is performed both numerically as well as experimentally. In the tests, the leading edge is clamped, while the trailing edge is loaded at the location and in the direction indicated by the arrow in Figure 7. The strain in the core of the airfoil profile is monitored in 6 different locations by single-element strain gages, while the displacement of the trailing edge is monitored by a LVDT transducer. The location of the strain gages has been chosen based on a finite-element model of the structure, which predicts the elements undergoing maximum strains for the considered loading configuration. A loading-unloading cycle is carried out on the basis of the results from the numerical model. Strain gauges location and loading curves for the case of 3 cells across the thickness and *L/R*=0.6 are shown in Figures 7 and 8. The absence of residual deformations confirms the finite-element model predictions, and demonstrates the capability of the chiral airfoils to undergo large deflections within the elastic range of the material. The comparison between the deflection performance of the 3 considered configurations is presented in Figure 9, which shows how the *L/R*=0.6, with 2 chiral cells provides the highest compliance, and how simple core changes, as a result of variations in the number of cells and in the *L/R* ratio can lead to significantly stiffer designs.
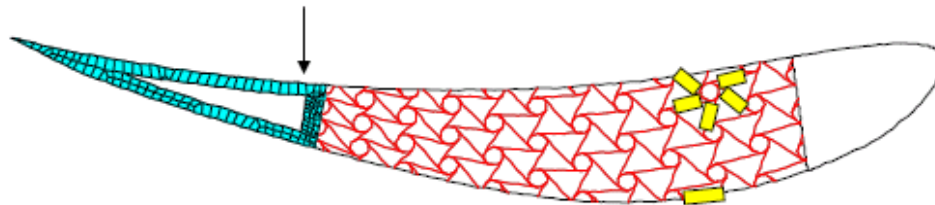

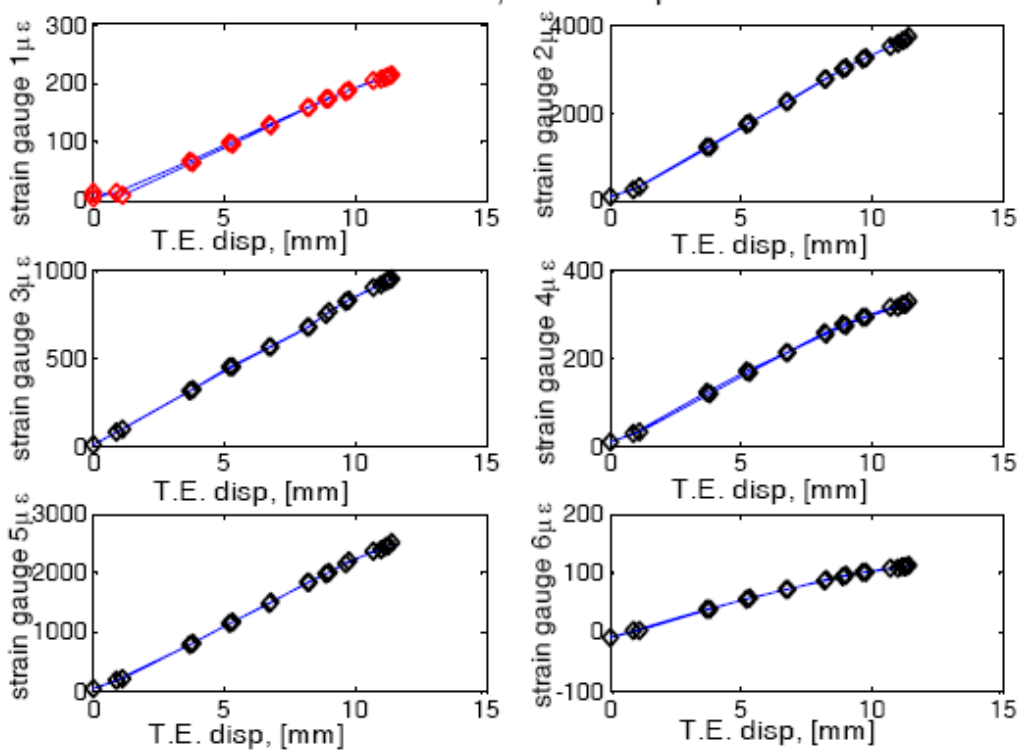Figure 7: Strain gauges and load location for test validation on the L/R=0.6, 3 cell sample

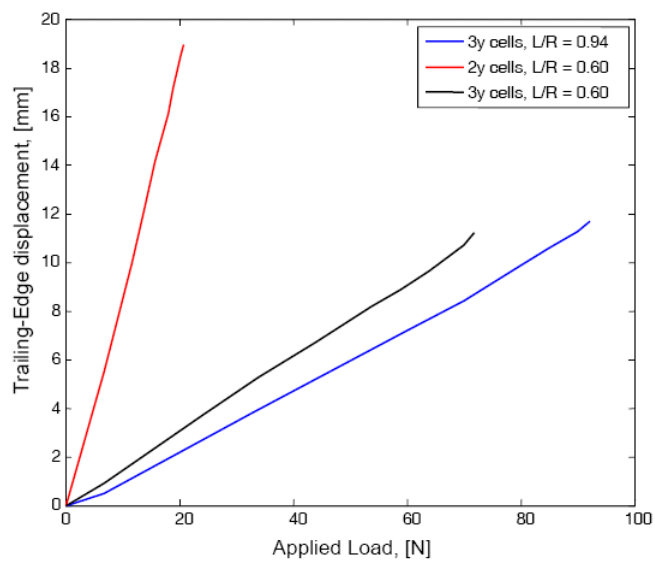Figure 8 - Experimental deflections and strains during loading cycles

Figure 9 – Comparison of deflections for the 3 tested samples

4.2. Dynamic morphing of chiral truss-core airfoils

The dynamic properties of chiral truss-core airfoils have been also investigated. The objective is to evaluate the potential of this configuration for dynamic shape control. In particular, operational deflection shapes obtained through localized dynamic actuation are evaluated to assess whether local deformations of the skins can be achieved. The feasibility of this concept has been previously investigated on simple beam models, and on numerical airfoil models. The numerical predictions are here compared to experimental results in an effort to validate the behavior observed in the numerical simulations. The experimental set-up shown in Figure 10 is used for the experiments. A selection of the obtained results is presented in Figure 11, which shows how localized deformations clearly appear on the upper skin of the airfoil. The location of such localized deformations changes with the excitation frequency, as shown with good agreement both by numerical and experimental results. This phenomenon could be exploited to affect dynamically the boundary layer, and could represent an alternative with respect to the application of synthetic jets, which have been proposed in the literature.
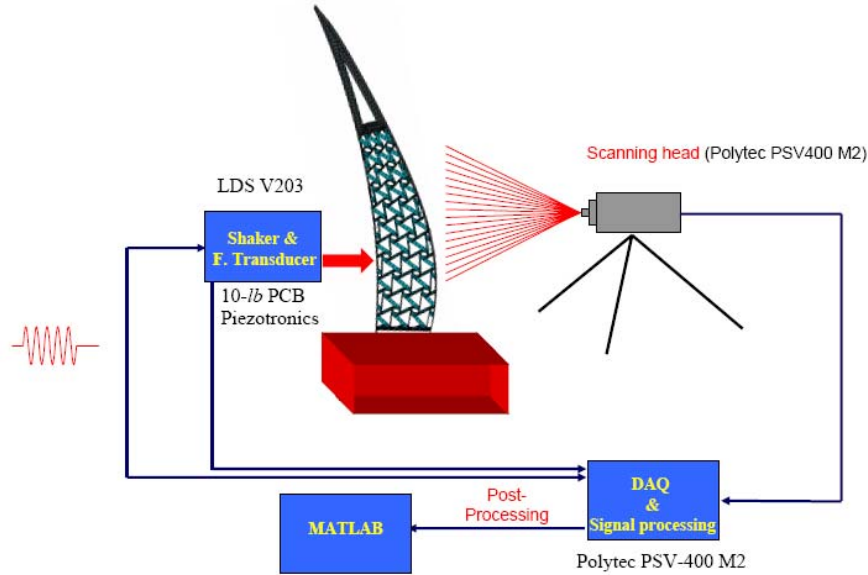

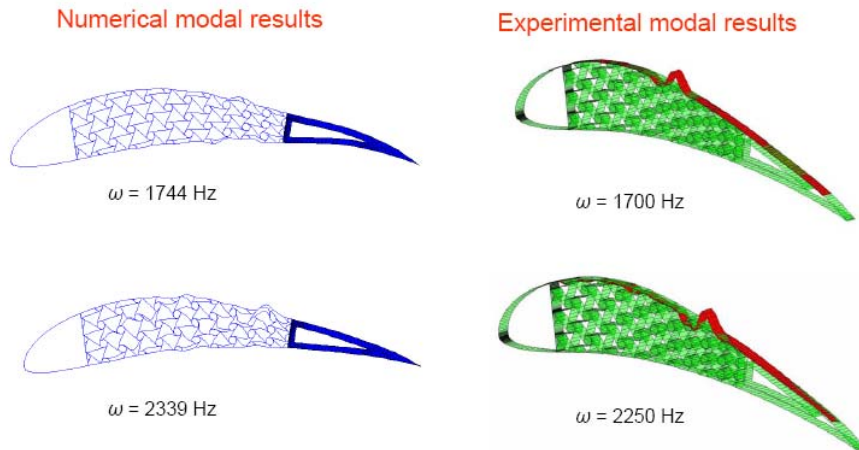Figure 10 - Set-up for dynamic testing of chiral core airfoils.

Figure 11 - Experimental and numerical dynamic deflection shapes at selected frequencies

5. Research Accomplishments on Novel Honeycomb Configurations

5.1. Flat-wise compression of chiral honeycombs

The flat-wise compression of a chiral honeycomb assembly is investigated through a linear elastic FE model. Linear buckling has in fact been identified in the literature as one of the failure mechanisms for traditional hexagonal honeycombs under flat-wise compression. Flat-wise strength is one of main properties for sandwich structures, as it is a measure of their crashworthiness. The study is performed by considering an infinite assembly whose behavior is defined by a unit cell connected to its neighboring cells through periodic boundary conditions. The unit cell is loaded by a downward unit force along the *z* axis. The effects of various parameters that define the geometry of the unit cell are investigated, and results for varying rib length to node center ratios *L/R* are here presented. The performance of the chiral configuration is compared with the compressive strength of traditional hexagonal and re-entrant honeycomb structures, which have been proposed to increase the compressive strength of traditional hexagonal honeycombs. The buckling strength of the two cellular configurations is compared in terms of the critical stress normalized with respect to the corresponding relative density, so that a normalized equivalent strength is considered. The comparison is presented in Figure 12, which demonstrates that the previously documented increase in strength for re-entrant honeycomb is only associated to an increase in the relative density, which translates into a weight increase. On the contrary, chiral honeycombs of various designs outperform the hexagonal configuration, particularly as the ratio *L/R* increases. It is worth noting how this improvement is the result exclusively of the geometry of the structure, and it is not associated to any weight increase. The chiral geometry is thus an excellent candidate to replace hexagonal cores in the design of crashworthy sandwich components.
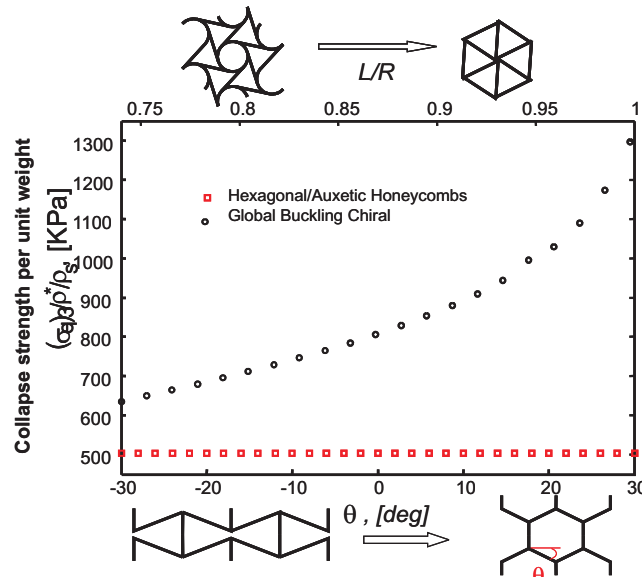

Figure 12 – Flat-wise strength of chiral and hexagonal honeycombs

5.2. Thermal performance of chiral honeycombs

These investigations continue from the previous reporting period. Metallic TPS are sandwich panel honeycombs characterized by the familiar hexagonal geometry, or a derivative thereof. In here we investigate the application of chiral honeycombs as an alternative configuration for sandwich design. Due to its widespread use, the hexagonal honeycomb is chosen as a reference for comparison with chiral honeycombs. The configuration for the hexagonal honeycomb is depicted in Figure 13.a, while the considered chiral honeycomb is shown in Figure 13.b. An analysis is performed through a FE model of the unit cells shown in the figures above. Proper periodic boundary conditions are applied to the unit cell to simulate the behavior of an infinite panel. Both conduction and radiation are included in the formulation. It is assumed that conditions may be such that the thermal boundary conditions are specified as temperatures as opposed to heat fluxes. In the analysis, the temperature at the exterior face sheet is assumed to vary linearly with respect to time, while the opposite face sheet of the sandwich panel is assumed to have zero heat flux. The temperature is set to increase linearly over time, with an initial uniform temperature of 293° K, at a rate of 8.6° K/s, which is comparable with rates experienced during space re-entry. A schematic of the configuration considered in the analysis is shown in Figure 13.c. The results in Figure 14 present the increase in temperature on the top face sheet as a result of the temperature ramp imposed on the

lower face sheet. The plots indicate how the chiral honeycombs can be designed to outperform the hexagonal ones, in particular through proper selection of face sheet thickness and gage thickness of the honeycomb.
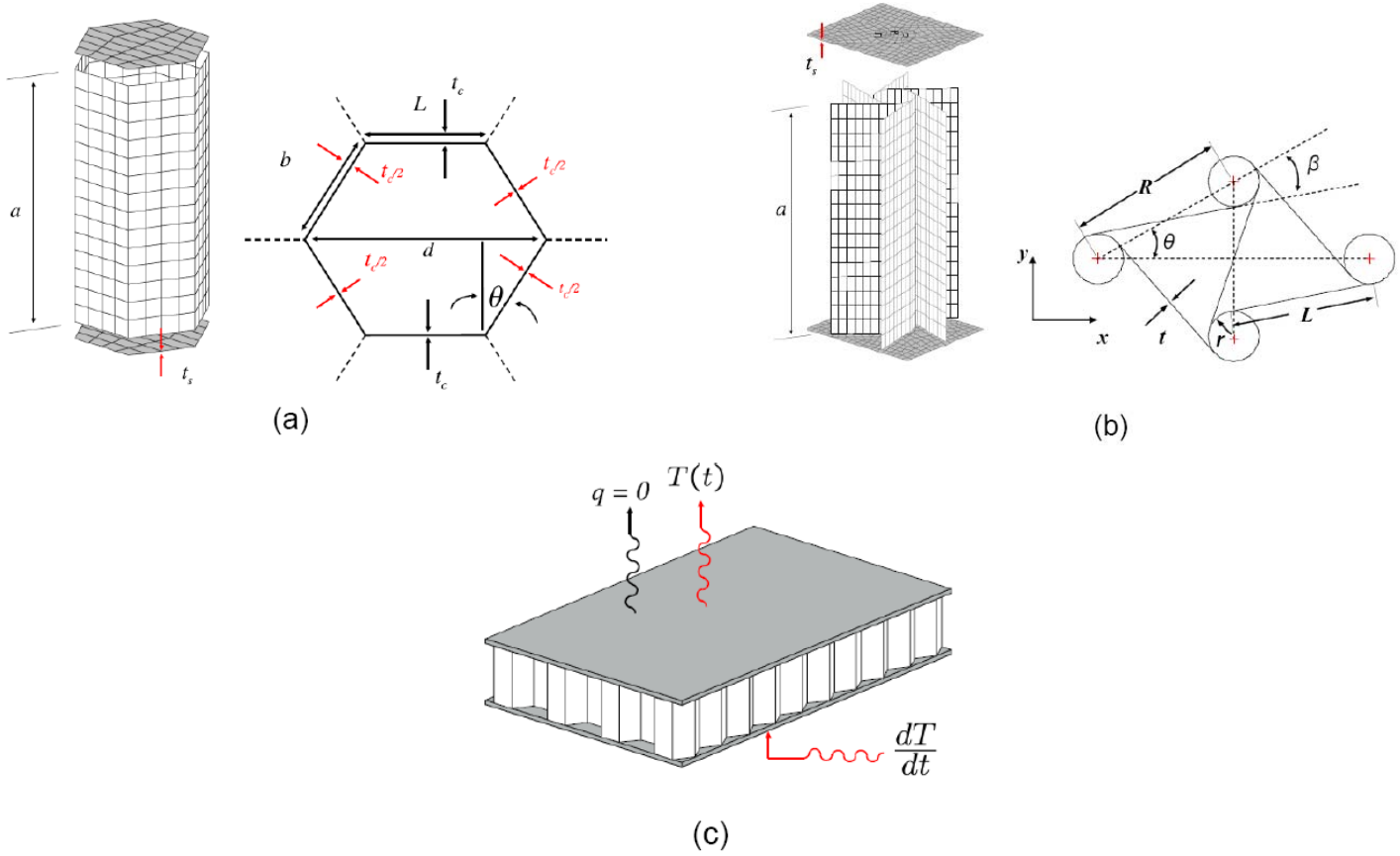

(a)

(b)

(c)

Figure 13 - Hexagonal (a) and chiral honeycomb unit cells (b).
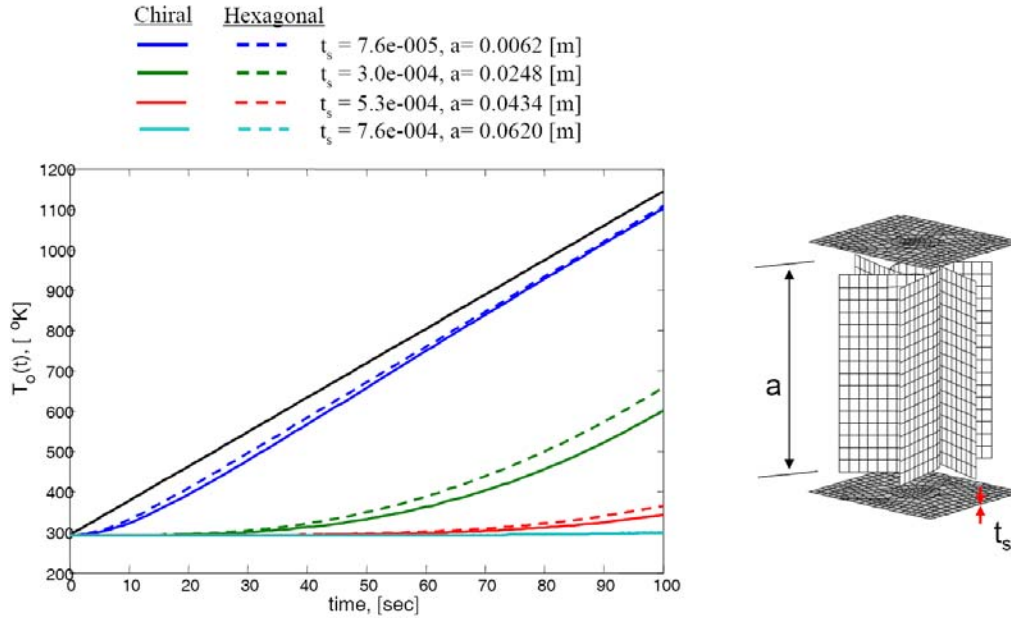Configuration for thermal analysis (c).

Figure 14 – Influence of face sheet thickness *ts* and gage thickness *a* on temperature time history

5.3. Evaluation of equivalent mechanical properties.

The evaluation of mechanical properties of chiral assemblies is particularly important to fully explore the realm of capabilities so far observed in various investigations. To this day, a limited number of studies have investigated

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in-plane mechanical properties such as Young's moduli and Poisson's ratios. Currently, analytical estimations of the deformation mechanism of a unit cell have been formulated to evaluate in-plane moduli, as well as in-plane Poisson's ratios. Moreover, numerical investigations are being employed to confirm results obtained from analytical models, and further guide the characterization of chiral assemblies. Currently, analytical models of elements composing chiral assemblies are being refined to include axial and shear deformations, in addition to bending deformations, on which all previous studies have been based. Such refinement provides additional insight into the mechanical behavior of chiral assemblies and may suggest additional, unexplored applications.

In-plane shear moduli are being estimated by analyzing the behavior of a single unit cell. Firstly, a numerical analysis is used to determine the characteristic deformation mechanism of a chiral lattice, a portion of which is presented in Figure 15. The resulting kinematics and kinetics associated with such deformations are determined, and are here presented in Figure 16. Previous models for in-plane moduli only considered bending of the ribs as the fundamental deformation mechanism. Current efforts have included both shear and axial deformations. To this end, the geometric model depicted in Figure 17 is discretized with a symbolic variational formulation; furthermore, the nodes or rings depicted in Figure 17 are assumed rigid as most of the strain energy is confined to the ligaments or ribs, as shown in Figure 18. In the variational formulation, this is achieved by imposing kinematic constraints between the nodes composing the circles and imaginary points at the circle centers. Displacements identical to those observed in numerical studies involving a full lattice are applied to the model shown in Figure 17. The resulting strain energy is equated to that of an equivalent continuum to obtain in-plane Poisson's ratios and moduli of elasticity. As an example, an analytical estimate for the relationship between in-plane Young's modulus E_x and geometric parameters is shown in Figure 19, where it is compared to the same estimate obtained from numerical models of a full lattice. In particular, numerical models of the full lattice have been produced to test the rigid-circle assumption. As shown in Figure 19, analytical models are able to capture both the case where circles are constrained to be rigid and the case where circles are allowed to deform. Results of numerical investigations confirm the validity of analytical models presented in Figure 19.
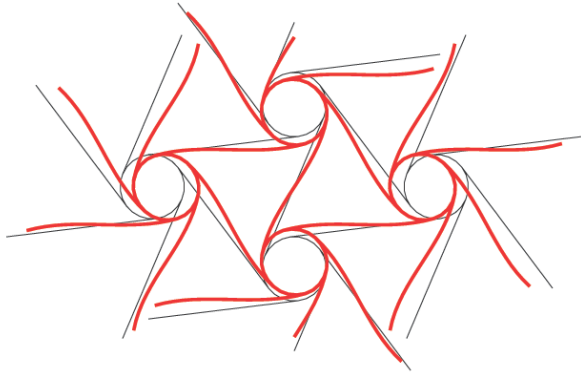

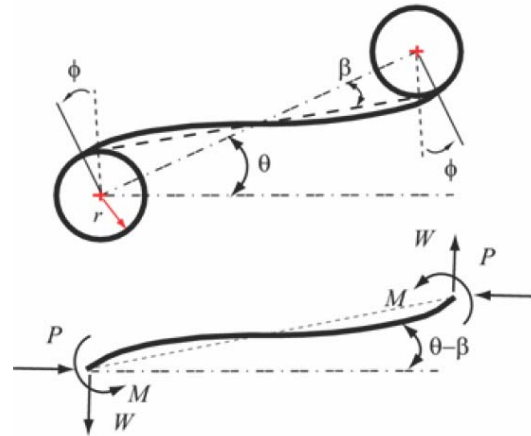Figure 15 – Deformation Mechanism

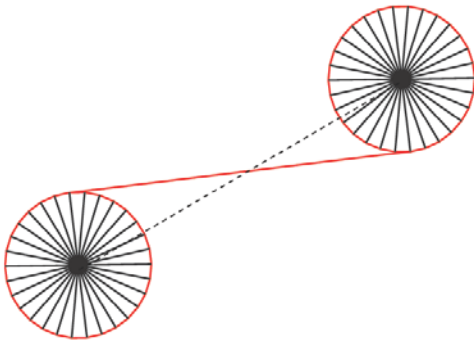Figure 16 – Deformation Mechanism explained
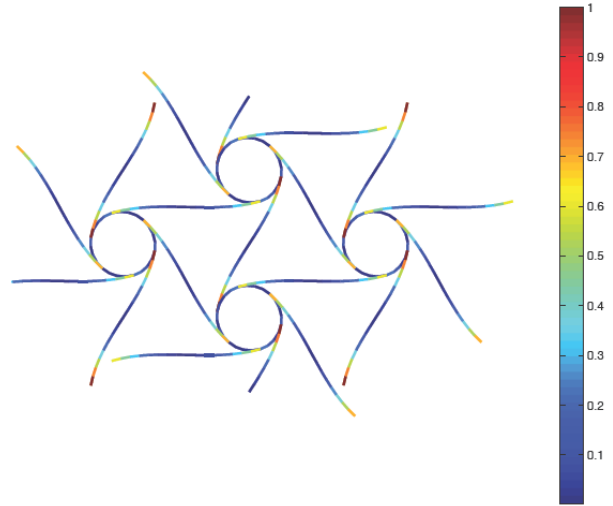

Figure 17 – Finite-Element Model

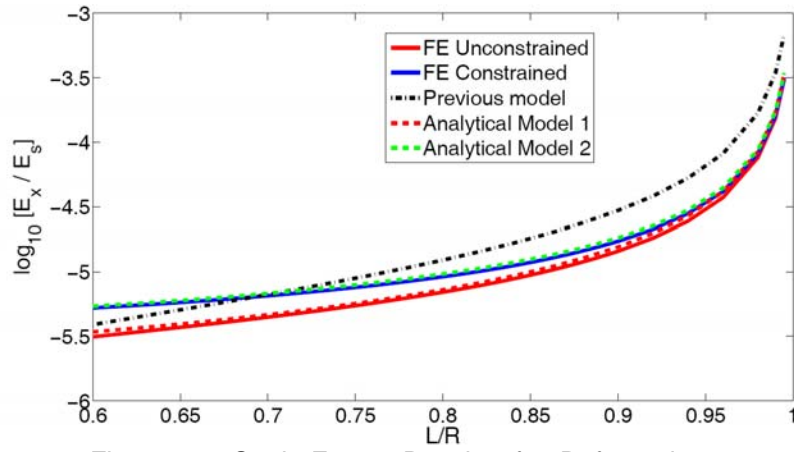Figure 18 – Strain-Energy Density after Deformation

11

Figure 19 – Strain-Energy Density after Deformation

5.4. Manufacturing of composite chiral honeycombs

These investigations continue from the previous reporting period, where manufactured metallic samples were presented and discussed. These promising results, obtained with a machined metallic structure, motivate the development of design and manufacturing processes for similar chiral structures made of composite materials. A fundamental reason for the choice of composites is the possibility to embed smart sensors and actuators in composite laminates so that the morphing capabilities of truss-core airfoils, for example, may be controlled actively. Moreover, composites allow the design of cellular assemblies with orthotropic stiffness and strength properties which may be exploited to enhance the performance and the design flexibility of chiral topologies. Finally, such investigations give the opportunity to study the manufacturing process and to evaluate its suitability for practical applications. The developed manufacturing process is based on the separate curing of thin ligaments and nodes with an autoclave vacuum bag process (Figure 20.a). The structural components are then assembled in a mould and bonded through a structural adhesive during a second curing process. The pressure between the adherents in the bonding process is exerted by the thermal expansion of silicon rubber inserts that have been shaped by pouring the liquid rubber before vulcanisation into the assembled mould (Figure 20.b).

Experiments will performed on the obtained composite chiral cells (Figure 21) in order to evaluate the stiffness and the ultimate strength of the structure as well as to identify its weakest structural points. Results will be correlated with FE analyses performed with different levels of detail, to account for delamination and damage progression in order to validate a modelling technique to be applied in the development of composite chiral structures.
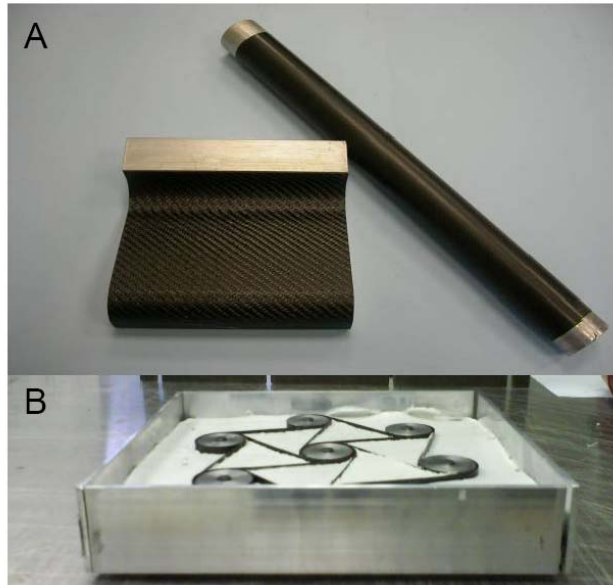

Figure 20 – Pre-cured nodes and rib elements (a) and assembled mould for the bonding process (b)

Figure 21 – Composite chiral cell

5.5. Analysis of in-plane wave propagation characteristics

Recently, the phenomenon of stop-bands or band-gaps in periodic structures has become the focus of significant efforts to uncover systems that can be tuned to control the transmission of mechanical energy. In periodic structures, the impedance mismatch generated by periodic discontinuities in the geometry, acting as a waveguide, and/or in the constituent material, causes destructive wave interference phenomena over specific frequency bands (band-gaps). The location and the extent of these band-gaps depend on the unit cell geometry. The chiral lattice as a periodic system (Figure 22) has the ability to inhibit transmission of mechanical waves over wide frequency regions. The band-gaps for chiral lattices are unexpectedly found at low frequencies, in contrast with traditional periodic assemblies such as hexagonal lattices. The determination of wave propagation characteristics is carried out employing Bloch's Theorem which is merely based on the application of periodicity conditions on forces and displacements of the unit cell. This results into an eigenvalue problem defining the relationships between in-plane wavenumbers and associated frequency of wave propagation. Such relationships highlight the band-gaps as frequency regions where the frequency/wavenumber relationship is not defined. Example of plots of such relations is shown in Figure 23. The frequency response function of a large finite-element model composed of many cells reveals the presence of the band-gaps as corresponding to extremely low vibrational response levels. Figure 24 presents results of parametric studies which investigate the location and extension of the band-gaps in terms of the geometry of the chiral unit cell. Experimental investigations are in the planning stages to verify the band-gap behavior and to estimate equivalent mechanical properties. Pictures showing the test specimen to be used for the validations are presented in Figure 25.
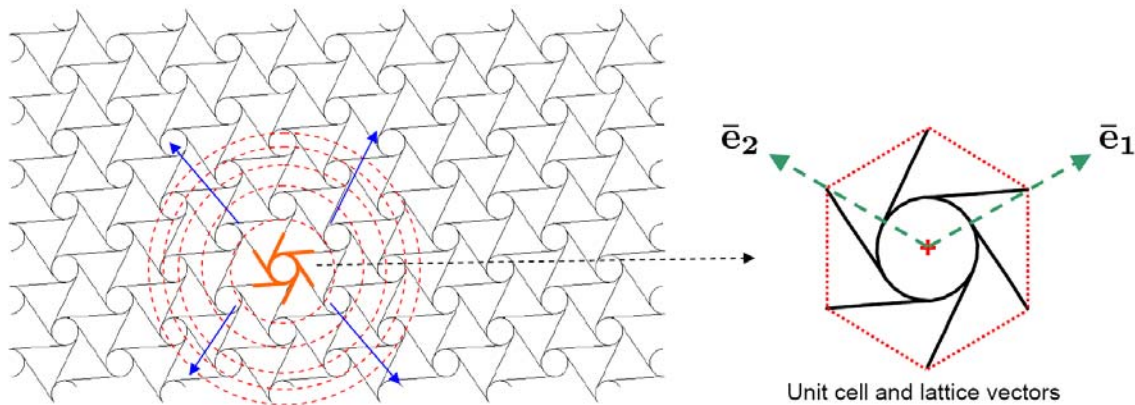

Figure 22 – Schematic of in-plane wave propagation configuration and considered unit cell geometry
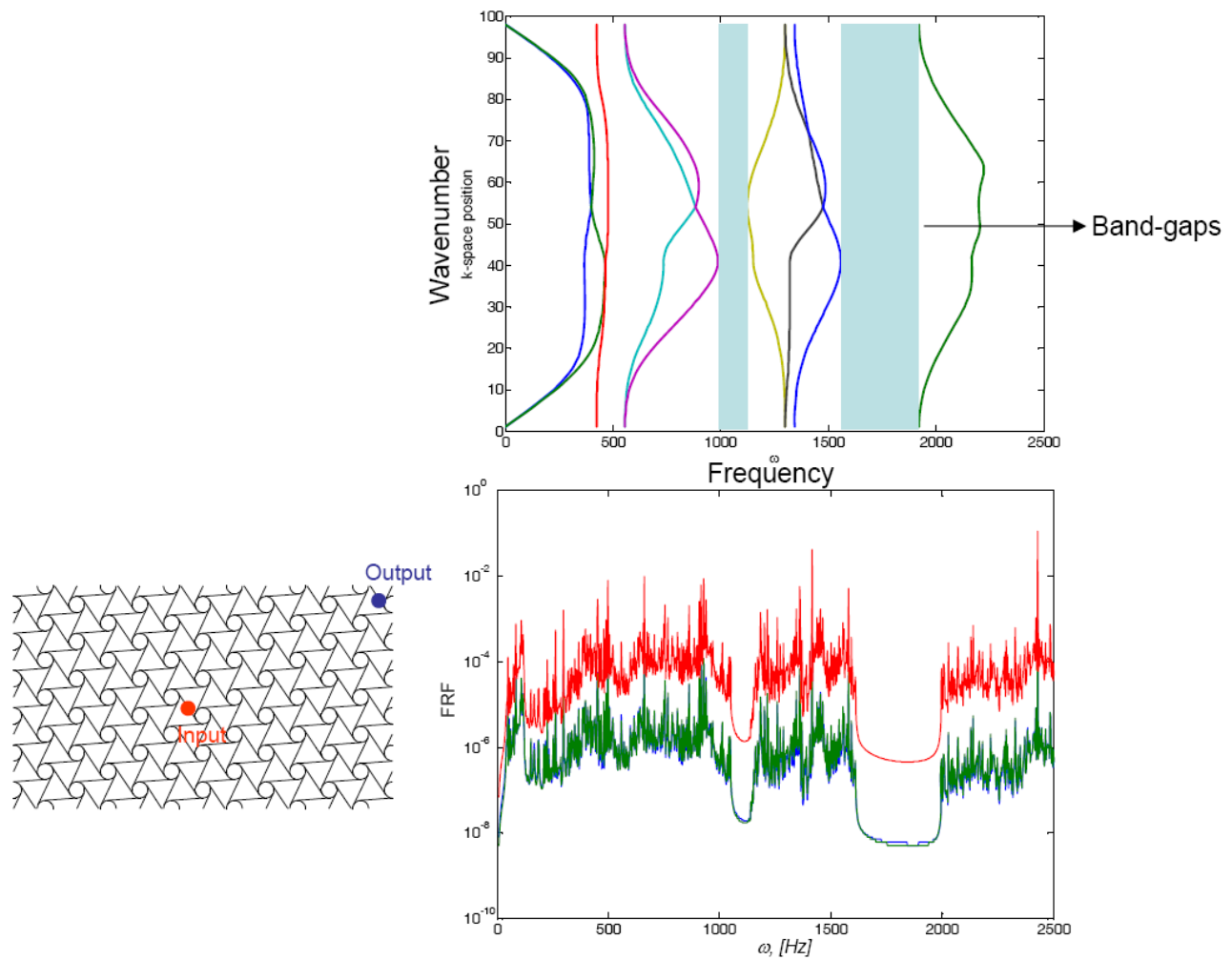
Figure 23 – Frequency/wavenumber relation for a chiral lattice.
Corresponding Frequency Response Function shows absence of mechanical response within bandgaps

$$t_c = Kt$$

$$t_c = Kt$$
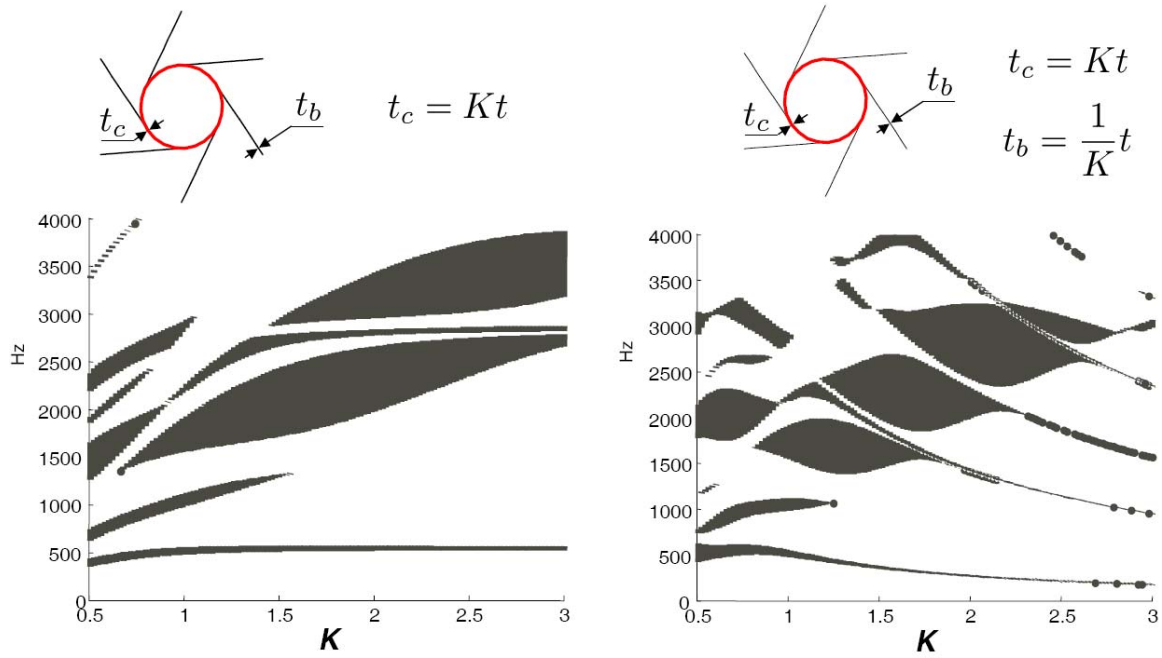
$$t_b = \frac{1}{K}t$$

Figure 24 – Variation of band-gaps in terms of unit cell geometry
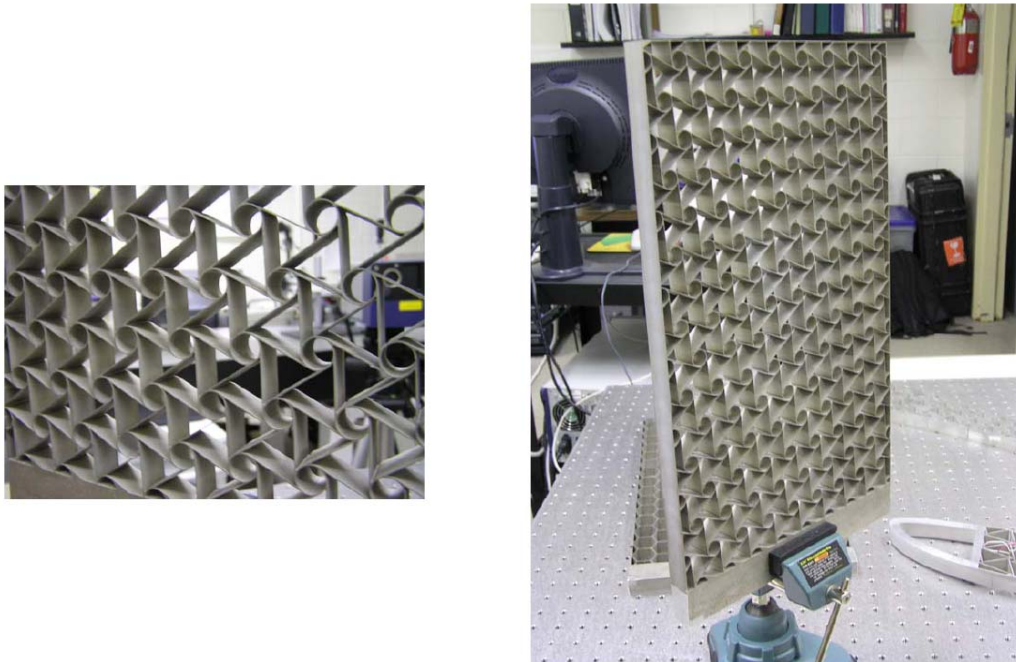

Figure 25 – Specimen for experimental investigation of wave propagation and evaluation of equivalent mechanical properties

6. Conclusions

The project investigates the application of the chiral geometry as part of a variety of structural concepts. The considered applications include exploratory research in the area of morphing structures, and a more applied study on a new honeycomb configuration.

The initial results on the morphing concepts are very promising and show that the proposed configuration is a viable alternative to the various designs proposed in the past by other researchers. The design flexibility offered by the chiral geometry provides the possibility of tailoring the compliance of the structure through simple selection of a limited number of geometric parameters.

The new honeycomb configuration under investigation can provide significant improvements in the mechanical performance of sandwich components, and may be considered for multifunctional designs. Its transition and practical implementation can be achieved in the short-term, after a complete characterization of its mechanical characteristics.

7. Publications

7.1. Book chapter

- Spadoni A., Ruzzene M., Scarpa F., "Static and Dynamic Properties of Chiral Core Airfoils", *AIAA – Recent Advances in Materials and Structures,* Under review January 2007.

7.2. Peer reviewed journal papers

- J. Martin, J.-J. Heyder-Bruckner, C. Remillat, F. Scarpa, K. Potter, M. Ruzzene "The hexachiral prismatic wingbox concept", Accepted Phys. Stat. Sol. (b), 1– 8 (2008) .
- Spadoni A., Ruzzene M., "Numerical and Experimental Analysis of The Static Compliance of Chiral Truss-Core Airfoils" Journal of Mechanics of Materials and Structures, Vol. 2(5) pp. 965, 2007.
- M. R. Hassan, F. Scarpa, M. Ruzzene and M. N. Mohammed. "Smart shape memory alloy chiral honeycomb". Materials Science and Engineering A. In press.
- Spadoni A., Ruzzene M., 2006 "Static Aeroelastic Response of Chiral Truss-core Airfoils" Journal of Intelligent Material Systems and Structures, 5 2007.
- Spadoni A., Ruzzene 2006 "Structural and Acoustic Behavior of Chiral Truss-Core Beams" ASME Journal of Vibration and Acoustics, v 128, n 5, Oct. 2006, p 616-26.
- Spadoni A., Ruzzene M., Scarpa F., 2006 "Dynamic Response of Chiral Truss-core Assemblies" Journal of Intelligent Materials and Structures, v 17, n 11, November, 2006, p 941-952.
- Scarpa F., Blain S., Lew T., Perrott D., Ruzzene M., and Yates J. R., 2006 "Analytical And Experimental Analysis On The Elastic Buckling Of Hexagonal Chiral Cell Honeycombs" Composites Part A: Applied Science and Manufacturing Volume 38, Issue 2 , February 2007, Pages 280-289.
- Scarpa F., Pastorino P., Garelli A., Patsias S., Ruzzene M., 2005 "Auxetic Compliant Flexible PU Foams: Static and Dynamic Properties" Physica Status Solidi B 242, No. 3, 681–694.
- Spadoni A., Ruzzene M., Scarpa F., 2005 "Global and Local Linear Buckling Of Chiral Cellular Structures" Physica Status Solidi B 242, No. 3, 695–709.

7.3. Peer reviewed conference papers

- Spadoni A., Ruzzene M., "Experimental Investigation of Static Morphing of Chiral Core Airfoils", Proceedings of the IMECE06 Conference, Chicago IL, November 2006.
- Spadoni A., Ruzzene M., "Buckling and Thermal Behavior of Chiral Honeycombs." Proceedings of the IMECE05 Conference, Orlando FL, November 2005.
- Spadoni A., Ruzzene M., "Structural and Acoustics Behavior of Chiral Truss-core Beams." Proceedings of the IMECE04 Conference, Anaheim, CA, November 2004.

7.4. Conference papers

- M. Ruzzene, Spadoni A., Scarpa F., "Application of Chiral Structures to Morphing Airfoils", Proceeding of Auxetics2006, Exeter, UK, September 2006.
- F. Scarpa*, Hassan M.R., Ruzzene M. "Modeling and testing of shape memory alloy chiral honeycomb structures",* Proceedings of the Smart Materials and Structures Conference, San Diego CA, March 2006.
- Spadoni A., Ruzzene M., "Static Aeroelastic Response of Chiral Truss-core Airfoils", Proceedings of the ICAST05 Conference, Paris, France, October 2005.

- Lew T., Spadoni A., Ruzzene M., Scarpa F., "Chiral hexagonal cellular sandwich structure: a vibroacoutic assessment"" Proceedings of the Smart Materials and Structures Conference, San Diego CA, March 2005.
- Spadoni A., Ruzzene M., Scarpa F., "Dynamic Response of Chiral Truss-core Assemblies" Proceedings of the Smart Materials and Structures Conference, San Diego CA, March 2005.
- Spadoni A., Ruzzene M., Scarpa F., "Chiral Truss-Core Beams With Selective Actuation Capabilities For Shape And Vibration Control." Proceedings of the ICAST04 Conference, Bar Harbor ME, October 2004.